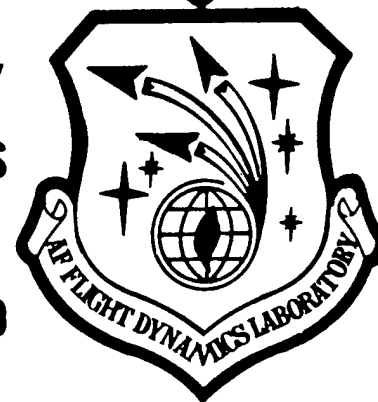# AIR FORCE FLIGHT DYNAMICS LABORATORY
DIRECTOR OF LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT PATTERSON AIR FORCE BASE OHIO

DETAILED MEASUREMENTS OF LINE SHAPE,
LINE SHIFT, AND SELF-ABSORPTION EFFECTS
ON STAGNATION ENTHALPY MEASUREMENTS
USING THE COPPER LINE INTENSITY RATIO
TECHNIQUE

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FEBRUARY 1978

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This report has been reviewed and is approved for publication.
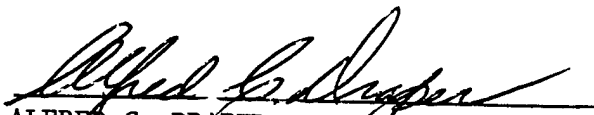
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FOREWORD

This technical memorandum is the result of a contract effort conducted by Dr. Anthony A. Boiarski of Battelle Memorial Institute, Columbus, Ohio. The contract period was from August, 1976, to October, 1977, and work was performed under a visiting scientist arrangement through the University of Dayton under Task No. 3 of Air Force Contract F33615-76-C-3145. This effort was conducted as an element of work unit 14260141, "Real Gas Diagnostics" of Project 1426, "Aerodynamic Ground Test Technology of the Experimental Engineering Branch, Flight Dynamics Laboratory. Mr. Hsue-Fu Lee, of the R&D Group was Contract Monitor and Work Unit Engineer.

The author wishes to acknowledge the efforts of Mr. Hsue-Fu Lee and Mr. Henry D. Baust of the Experimental Engineering Branch for their engineering assistance in setting up the experiment and test planning to acquire the spectroscopic data.

ABSTRACT

Spectral line intensities, line widths, and shifts of the copper lines at 5106 Å and 5153 Å were obtained while viewing the gas cap radiation from models in an arc-heated nozzle flow. These spectral features were then used to infer the enthalpy and copper density of the gas in the model stagnation zone. The measurements were performed in the Air Force Flight Dynamics Laboratory Re-Entry Nose Tip (RENT) facility for an arc stagnation air pressure of 100 atmospheres, an arc heater current of 2600 amps, and a Mach 1.8 contoured nozzle. Data was obtained for both high swirl (i.e., peaked) and low swirl (i.e., flat) enthalpy profile conditions.

From the above measurements, and line broadening calculations based on Lindholm's theory, the gas cap conditions were found to produce a high degree of self-absorption of the copper line radiation. Line intensity results, corrected for self-absorption using Lindholm's theory, showed that the average copper density was two orders of magnitude higher than required to justify an optically-thin assumption. Due to this high copper density, the corrected enthalpy of 4275 Btu/lbm was found to be 60 percent lower than would have been inferred from an optically thin analysis for high swirl arc conditions.

The absolute value of 5106 Å line width, as well as the ratios of 5106/5153 widths, ratios of line peak intensities, and overall shapes of the convoluted line profiles were all consistent with predictions based on Lindholm's theory. However, line shift-to-width ratio measurements for the 5106 Å line showed an anomalous blue shift which cannot be presently explained based on Lindholm's theory, shift calculations, and measurements of shift by other authors. This anomaly weakens the present results and prevents a clear error estimate from being given for the enthalpy measurements since the corrected enthalpy is dependent on the application of Lindholm's theory to account for self-absorption effects.

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LIST OF SYMBOLS

Symbol	Meaning
H_o	Stagnation Enthalpy in Btu/lb_m
I^m	Measured value of the peak copper line intensity for a given wavelength line
ℓ	Length of the radiating slab of high-temperature gas containing copper atoms
N_{Cu}	Number density of copper in atoms/cm^3
p, p_{t_2}	Gas-cap stagnation (i.e., impact) pressure in atmospheres
T	Gas-cap temperature in $^\circ$K

Greek

Δ^T	Instrument apparatus function full-width at half-height in $\overset{\circ}{A}$ (i.e., triangular shape)
Δ^ℓ	True line full-width at half-height in $\overset{\circ}{A}$ independent of line shape
Δ^m	Measured line full-width at half-height in $\overset{\circ}{A}$ (i.e., convolution of true line profile and instrument apparatus function)
δ	Line shift from zero pressure broadened condition in $\overset{\circ}{A}$ (i.e., positive value indicates a shift to longer wavelengths)

I. INTRODUCTION

The Air Force Flight Dynamics Laboratory (AFFDL) is developing ground-based facilities capable of simulating the environment experienced by nose tips of reentry vehicles. One such device is the AFFDL Reentry Nose Tip (RENT) facility. In order to utilize such a facility to its greatest potential, the characteristic flow properties must be adequately defined. A flow property of particular interest is the stagnation enthalpy, H_o. Attempts have been made to insert physical probes into the flow to measure this quantity, but they have not been entirely satisfactory due to the very high heating rates encountered in the RENT flow.

An alternate approach, which has received a good deal of attention, is a spectroscopic technique involving measurement of atomic line radiation from copper that is present as a contaminant in the stagnated flow on the model nose tip. Several in-house exploratory studies have been performed to investigate the use of this technique to measure stagnation enthalpy in the RENT facility employing a line ratio method[1,2]. In reference 1, a rapid scanning spectrometer was used to obtain low resolution spectra of copper emissions from a model nose tip over a broad spectral region. The 5106 Å, 5153 Å, and 5218 Å copper lines were ultimately identified as being the most useful spectral features for analysis. However, sequential scans of these lines indicated large fluctuations in the 5153 to 5218 line intensity ratio. Theoretically, this ratio should have remained constant due to the small difference in the upper energy levels of these two lines. This observation led to the conclusion that[2]:

- The scanning spectrometer was not stopping the action in the flow field (i.e., line intensities were fluctuating faster than the 20 μsec scan time between spectral lines).

- Copper number density fluctuations, self-absorption effects, or both, were occurring which preferentially changed the intensity of one of the selected lines.

In reference 2 the first conclusion was tested by monitoring the variation in intensity of the 5106 Å line with time using a monochromator. It was found that one order of magnitude intensity fluctuations occurred in times of 1 millisecond but that only 10-20 percent intensity variations were measured in the 20 μsec line-to-line scan time frame of the rapid scan spectrometer. These small fluctuations in a single line did not explain the large fluctuations in the 5153/5218 intensity ratio noted in reference 2.

Continued studies at AFFDL[3] centered around the experimental use of an in-house developed polychromator to make real-time measurements of the 5106 Å and 5153 Å line intensities in order to establish if self-absorption, or copper density fluctuations, or both, were responsible for the anomalous spectral results reported reference 2. However, use of the polychromator technique for spectral data acquisition led to ambiguous results because this instrument could not distinguish the above effects from the possible existence of intensity fluctuations due to line shape and line shift variations.

Theoretical investigations were also undertaken at AFFDL to supply a method of correcting the line spectra for self-absorption effects and to calculate a quantitative error estimate for the line ratio technique[3]. This theory calculated integrated line intensity only (i.e., no line shape or shift results were computed). Polychromator data utilizing the 5106/5153 line ratio and the absolute intensity of the 5106 Å line were then used in conjunction with the theoretical calculations to show qualitatively that the optically thin assumption was invalid[3]. However, quantitative corrections for self-absorption were hampered by the fact that line shift and line shape changes were not accounted for in the polychromator intensity measurements.

The main purpose of the study being reported herein was to ascertain the quantitative effects of self-absorption, line shift, and shape change on the overall enthalpy measurement utilizing the copper line technique. A secondary objective was to attempt to make a proper correction for such effects so that accurate enthalpy results could still be obtained in the RENT environment. Finally, the shift and shape change information were used to check the validity of utilizing the polychromator method for recording the raw line-intensity data. To accomplish these tasks a new technique was chosen to obtain copper line spectra. Using this method, the entire 5106 Å and 5153 Å

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line spectrum was obtained simultaneously. This spectrum was obtained under conditions of high spectral resolution such that line shapes, widths, and line shifts could be determined for the 5106 Å and 5153 Å lines. Furthermore, this spectrum was obtained in a time scale compatible with the requirement for instantaneous measurements (i.e., data gathering times of the order of 10-20 μsec). Also, the AFFDL copper line computer program was modified to include the calculation of line shape and shift of the copper lines of interest in order to correct the 5106/5153 line ratio for self-absorption effects.

II. EXPERIMENTAL SETUP

The experimental apparatus used to obtain copper, Cu, line spectra in the RENT facility is shown schematically in Figure 1. Radiation from the model nose cap was collected by a 10-cm-focal-length lens, 2.5 cm in diameter. This lens was located 30.5 cm from the model centerline and it focused the collected light onto an 8-mm-diameter coherent fiber-bundle face. A heat reflecting mirror was placed in front of this collection lens to minimize heating effects due to radiation from the high-temperature model. A photograph of the light collection system is shown in Figure 2. Note the adjustments available for positioning the point of light collection and setting the lens focus.

The nose-cap radiation was then transferred through 3 meters of the fiber bundle onto the optical rail of a Jarrell-Ash 3/4-meter spectrograph. Cu line radiation exiting the fiber bundle was then collected and focused onto the spectrograph slit with a 13-cm-focal-length, 9.5-cm-diameter lens which was located 96 cm from the slit. An order sorter filter (not shown in Figure 1) was also placed in front of the slit to block light at wavelengths less than 5000 Å. Taking into account entry losses and absorption in the fibers, 25 percent of the initial radiation incident on the collector lens was transferred to the spectrograph slit with the present lens/fiber-bundle optical system.

This fiber-optics-based light transfer system was used to avoid long-optical-path vibration effects and as a fire safety precaution because the fiber bundle was passed through a small hole in the facility door frame and the door closed during testing.

Several other items were located on the spectrograph optical rail as shown in Figure 1 and the photograph in Figure 3. A removable mirror temporarily interrupted the optical path from the model nose cap. This mirror was used to direct the light from various calibration sources, also shown in Figure 3, onto the spectrometer entrance slit. A rotating mirror and condensing lens were used to select and focus radiation from either of the two calibrating sources. One such source was a Standard Lamp (STD Lamp in Figure 3). This was a tungsten ribbon lamp that had been calibrated against a similar lamp at the National Bureau of Standards. The

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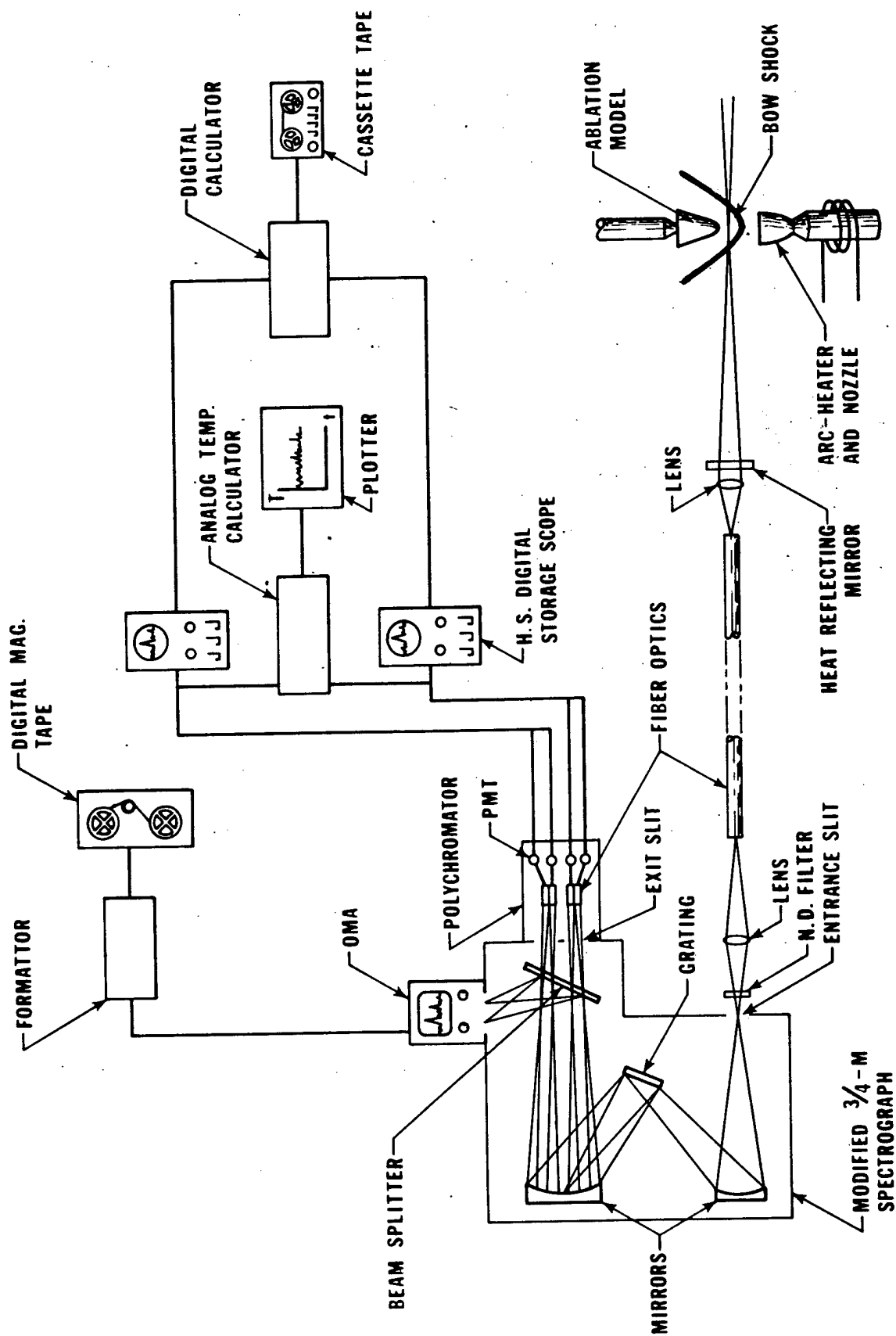
FIGURE 1. BLOCK DIAGRAM OF EXPERIMENTAL SETUP

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POSITION ADJUSTABLE HOLDER

8mm COHERENT FIBER BUNDLE LIGHT TRANSFER CABLE

"HOT" MIRROR, COLLECTOR LENS INSIDE TUBE
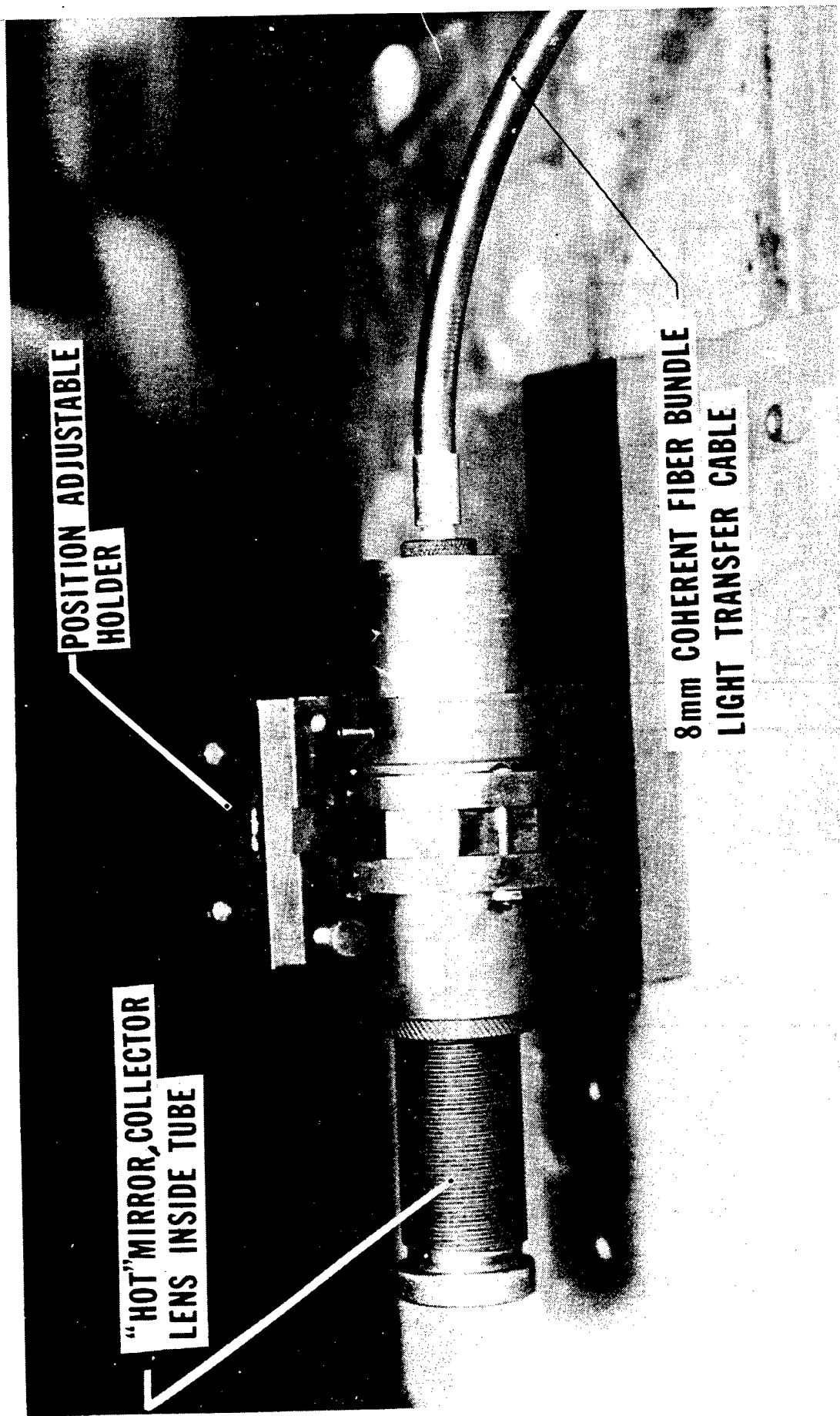
FIGURE 2. LIGHT COLLECTION AND TRANSFER SYSTEM

SPECTROGRAPH ENTRANCE SLIT

REMOTE-OPERATED NEUTRAL DENSITY FILTER WHEEL

REMOVEABLE MIRROR

LENS

CU HOLLOW CATHODE

ROTATING MIRROR

LENS

STD LAMP

FIBER OPTICS TIP

FIGURE 3. IMAGE TRANSFER AND CALIBRATION SYSTEM

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absolute light output of the lamp at various wavelengths is published for a lamp current of 35 amperes. This lamp was used to calibrate the various detectors that recorded the copper line intensities. The other calibration lamp was a copper hollow-cathode lamp which was used to generate a known copper spectrum. This calibration spectrum was required in order to align the various light detectors and to ascertain the spectral position of the copper lines prior to and after a tunnel run. This baseline position information was also used to infer line shift information during the arc tunnel tests.

Another piece of apparatus located on the spectrograph optical rail was a remotely-operated, neutral-density filter wheel (see Figures 1 and 3). This device was used to remotely attenuate nose-cap radiation in case a detector was overloaded with incoming signal during an arc-tunnel run.

After passing through the spectrograph slit, the incoming radiation was collimated and diffracted using a 1180-grooves/mm grating in the first order. This grating was blazed at 7500 Å. The spectrally analyzed radiation from the grating was then refocused onto t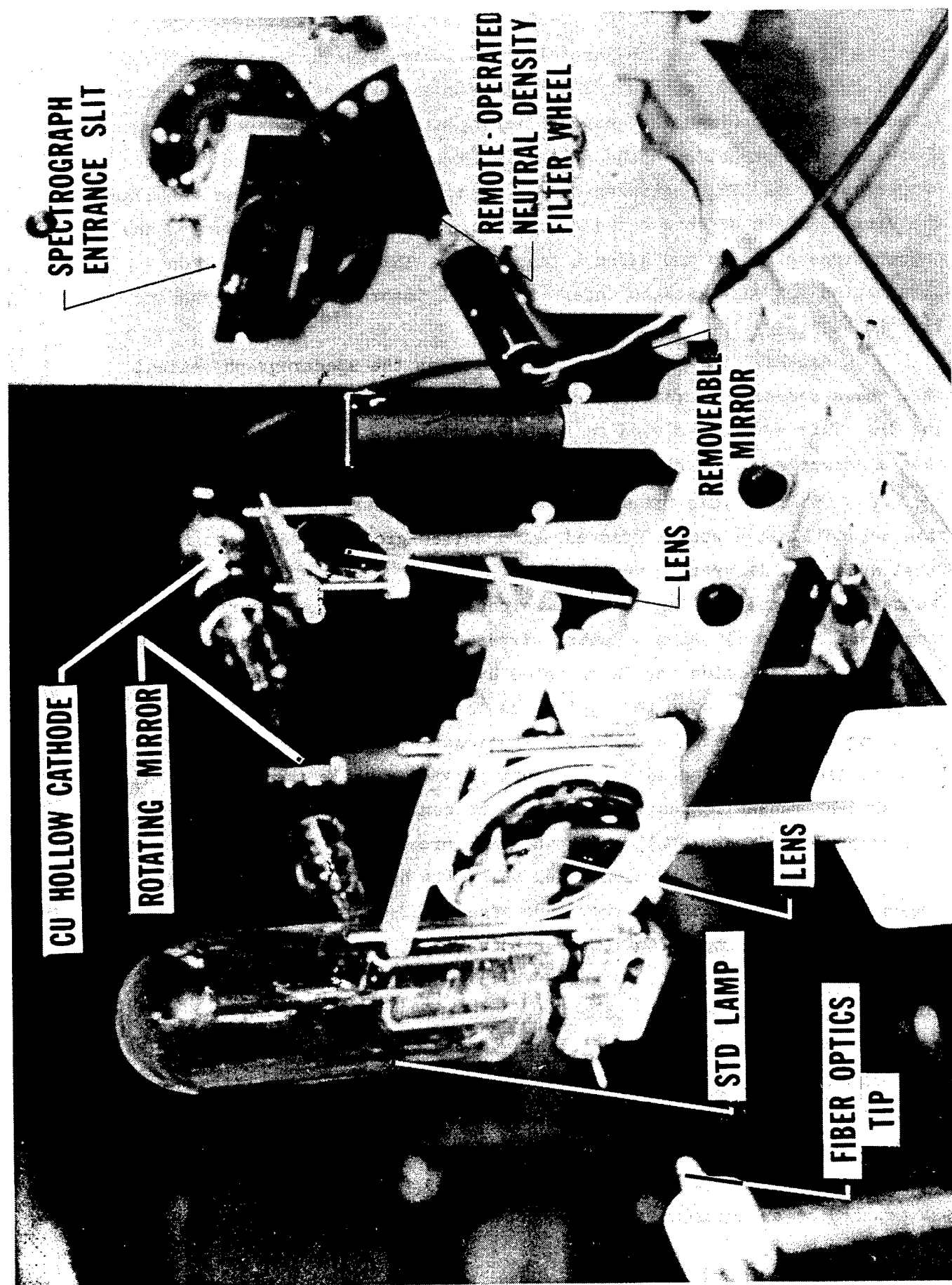he spectrograph exit plane (see Figure 1) using a camera mirror. Before reaching the exit plane, however, this radiation was interrupted by a 90/10 Pellicle beam splitter. The spectrograph was modified to include this splitter so that two data gathering methods could be employed simultaneously. Ten percent of the incident light was directed toward a polychromator while the majority of the incident radiation was focused onto the sensing screen of an Optical Multichannel Analyzer (OMA), as shown in Figure 1.

The polychromator consisted of a slit holder with four slits ganged together in groups of two. One of each of these pairs monitored 5106 Å and 5153 Å line intensities, respectively, and the other monitored the background light in the region of each of these lines. Each slit group could be independently translated along the focal plane of the spectrograph to independently adjust the position of the slit pair in order to accurately position the slit using the copper hollow-cathode calibration lamp. Two-hundred-μm fixed slits were utilized in the present tests. A photograph of the Pellicle splitter assembly, OMA, and polychromator slit holder is shown in Figure 4. Note in this figure that the slit holder was mounted on an adjustable tower to obtain accurate focusing of the

SLIT HOLDER

CAMERA MIRROR

FOCUSING TOWER

BEAM SPLITER ADJUSTMENT ASSEMBLY
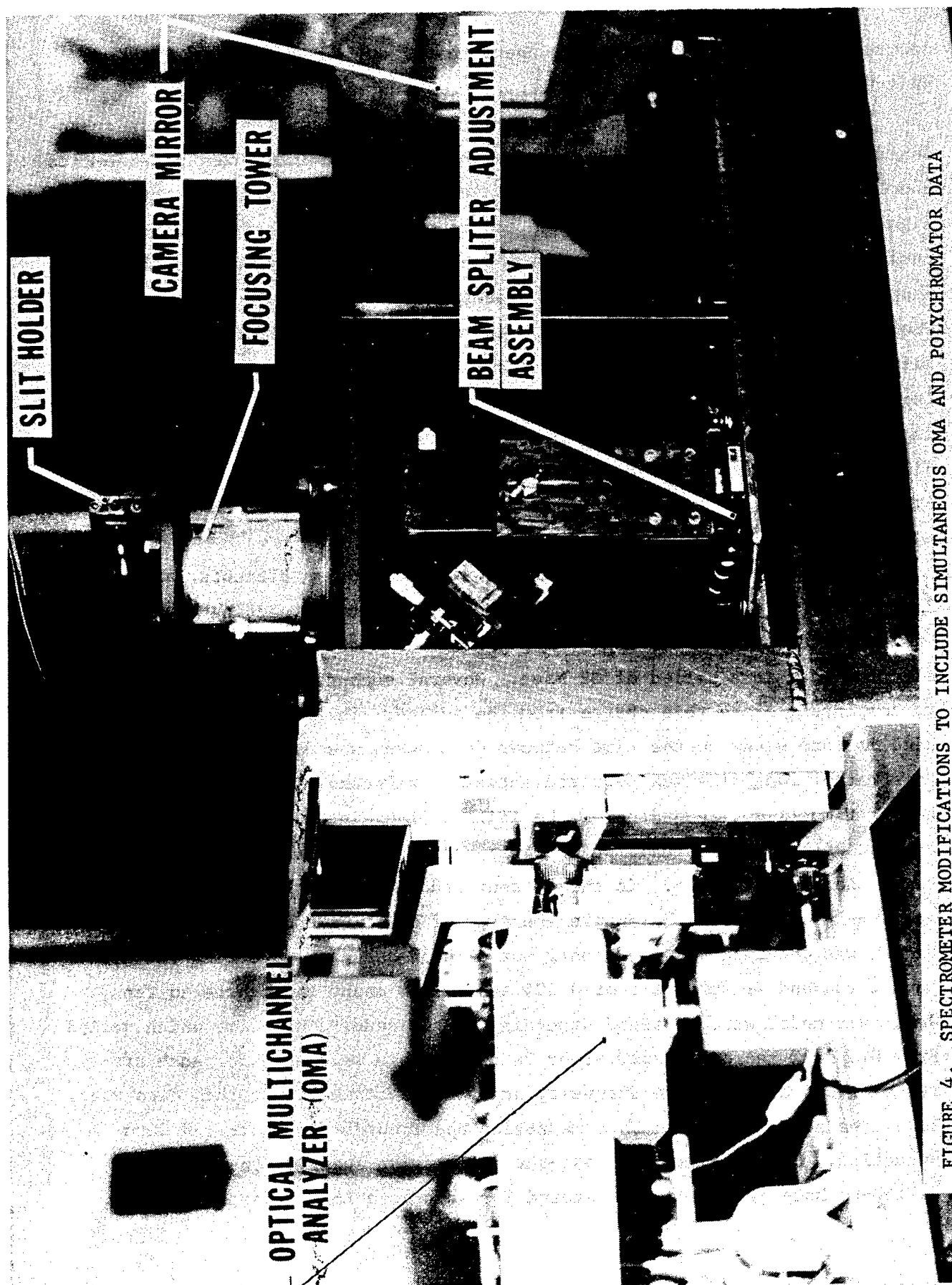
OPTICAL MULTICHANNEL ANALYZER (OMA)

FIGURE 4. SPECTROMETER MODIFICATIONS TO INCLUDE SIMULTANEOUS OMA AND POLYCHROMATOR DATA

spectrograph camera mirror with respect to the exit-slit plane of the polychromator.

After passing through the polychromator slits, the light was transferred to 1P28 photomultiplier tubes using four short incoherent fiber-optics bundles. The photomultiplier tubes converted the light into an electrical signal which was amplified and then stored in various high-speed digital oscilloscope memories. Data stored in the volatile memory of the oscilloscope was transferred to permanent cassette tape storage via a Hewlett Packard digital calculator after an arc-tunnel run was completed. The intensity and background signals could also be fed to an analog temperature calculator (see Figure 1) developed at AFFDL for instantaneous conversion of intensity data to an optically-thin temperature associated with the 5106 to 5153 Å line intensity ratio. For details concerning the photomultiplier's, amplifiers and the analog temperature calculator, the reader should consult Reference 4.

The OMA consists of a screen with 500 sensing elements located 25 μm apart in a linear array. Light incident on these sensing elements was converted to an electrical charge which was scanned off by a sweeping electron beam in a period of 32 msec. Several such time scans are required to completely erase this charge from the screen. In fact, seven scans were used in this study so the time between data scans was 0.224 sec. Although this rather long time was required between data scans, the actual data-taking time (i.e., recording of the initial light intensities) was controlled with a high-voltage pulser that had a variable shutter time down to as short as 50 nsec. In the present study, 10-50-μsec shutter times were employed. Hence, the entire spectrum of the 5106 and 5153 Å copper region was obtained simultaneously for a 10-50-μsec period during the arc-tunnel run and at intervals of 0.224 sec. This meant that three to ten scans per model were obtained depending on the model dwell time which varied from 0.5 to 2 sec per model. Four to five models were used for each arc-tunnel test so 12-50 line intensity scans were obtainable at this data rate. Each line scan was stored on a magnetic tape recorder for post-run data reduction. Several pre- and post-run calibration scans of the copper hollow-cathode lamp were also stored for later use in the data reduction.

III. ARC-FACILITY TESTING

A. Pre-Run Setup and Calibration

Prior to an arc-tunnel run, the OMA was temporarily removed and a flood lamp was placed at the exit plane of the spectrograph. This lamp provided a back light for the optical system such that an image of the entrance slit appeared at the tunnel exit plane. The image size was 1 mm long and 0.05 - 0.1 mm wide. The image position and focus were then checked with respect to the tunnel axis. Image position was adjusted in order to center it on the nozzle axis at a position 1.27 mm (0.050 in.) downstream of the nozzle exit plane with the longest dimension perpendicular to the nozzle axis. During a tunnel run, the models were held in position 2.54 mm (i.e., 0.10 in.) from the nozzle exit plane using a servo-positioning system driven by heat sensors pointed at the nose-tip material being ablated by the arc-heated gas flow. This arrangement put the slit image 1.27 mm off the receding graphite model nose-tip surface, between it and the detached bow shock wave.

Just prior to the arc-tunnel run, several OMA spectral scans were stored using the copper lamp spectrum as a calibration source. The polychromator slits were then adjusted to center the appropriate slits on their respective copper lines. After these tasks were completed, the polychromator amplifiers were zeroed with no light on the photomultiplier tubes. Finally, the standard lamp was turned on and the polychromator amplifier gains were adjusted to a position which gave an appropriate output (i.e., constant in this case). This latter adjustment was required because of the differences in transmission of the various fiber bundles as well as gain differences in the four photomultiplier tubes. After turning off the standard lamp and extracting the removable mirror, the diagnostic system was ready for taking copper line intensity data during the actual arc-tunnel test.

A remote switch was used to initiate the taking of intermittent (i.e., approximately five times/sec) OMA data during the tunnel run. Poly-chromator data storage was controlled by the digital oscilloscope sweep time and manual trigger to start the sweep. Post-run OMA data were also obtained using the Cu lamp.

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B. Preliminary Tests

After the Data Gathering System was installed in the RENT facility, preliminary data were obtained using the copper hollow lamp as a source during an actual in-house tunnel test. The purpose of these experiments was to ascertain what effects the electromagnetic and acoustic noise environments had on the data acquisition systems. It was found that the OMA output was affected by acoustic noise and its associated mechanical vibration. Direct mechanical vibration from water pumps and water flow also had a deleterious effect on OMA performance during a tunnel run. Vibration isolation of the spectrograph from its steel table mount was tried first using variable pressure vibration mounts. This direct isolation reduced but did not eliminate the interference. Next, an aluminum sheet metal enclosure was fabricated to cover the top and sides of the spectrograph and instrument rack. Leaded vinyl sheet was attached to the inside of these aluminum enclosures and then foam pad was added to the vinyl sheet. Foam only was also attached to the plates on which the spectrograph and instrument rack were sitting. Hence, these instruments were completely surrounded by some acoustic material. Further, vibration isolation of the instrument rack was also accomplished using two layers of Isofoam rubber pad material sandwiched between aluminum plates between the instrument rack and the floor.

The above measures reduced the acoustic vibration interference on the OMA system to a negligible amount. They also eliminated grating vibration which had affected the polychromator performance. These system alterations enabled the continuation of copper-line spectral analysis from arc-tunnel induced/gas-cap radiation.

C. RENT Tests

Copper line intensity data were obtained from five arc-tunnel runs. Various types of graphite models, run conditions, model dwell times, etc., were employed during these initial tests. The common tunnel conditions are listed in Table 1, and a partial test matrix is given in Table 2. The shutter time and slit width listed in Table 2 refer to the OMA shutter and the spectrometer slit. Also shown in this latter table

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TABLE 1. TEST CONDITIONS (COMMON PARAMETERS)

$$I_{arc} = 2600 \text{ Amps}$$

$$V_{arc} = 9 \text{ KV}$$

$$P_o = 1500 \text{ psig (i.e. 100 atm)}$$

09111P Nozzle (0.9" diameter throat,
1.11" diameter exit, contoured)

TABLE 2. TEST SERIES MATRIX

Run Number	Date (1977)	Neutral Density Filler Transmission	Shutter Time, μsec	Slit Width, μm	Tunnel Enthalpy Profile	Model Material	Model Dwell Time, sec	Poly Data	OMA Data
91-020	8-23	1/5	50	100	Peaked*	AFML Adv. Graphite	~2	None	Good
91-021	8-24	1	25	25	Peaked	ATJ	~1	None	None
91-023	8-26	1	10	100	Flat**	ATJ-S	~1/2	Poor	Poor
91-024	8-26	1	50	50	Flat	ATJ-S	~1/2	Fair	Fair
94-022	8-30	1	10	50	Peaked	Adv. Graphite	~1	Good	None

* - High swirl mode.

** - Low swirl mode.

are remarks concerning the quality of the data from the various tests.
Run No. 91-020 was a so-called "peak" enthalpy profile run, and it was
the most successful from the standpoint of OMA data. Air Force Materials
Laboratory (AFML) high-quality advanced graphite models were utilized. All
the models had a 1/2-inch (1.27-cm) nose diameter. Long dwell times of
approximately 2 seconds enabled a good deal of OMA data to be obtained.
However, amplifier problems were encountered during this run, so no simul-
taneous polychromator data were obtainable.

For Run No. 91-021, no data at all were recorded. Post-run exam-
ination of models and video coverage of the run showed that test time was not
available. ATJ-S graphite was used for the remainder of the tests. These
models were 1/2-inch-diameter (1.27-cm) cylinders with flat and hemispherical
faces. Two flat- and two hemisphere-shaped tips were run on the two tests
to follow. The order alternated as flat-round-flat-round. These latter runs
employed the so-called "flat" enthalpy profile. OMA data taken during Run
No. 91-024 were of fair quality. Simultaneous polychromator data were also
obtained during these runs. Run No. 94-022 was a piggyback attempt on some
actual nose-tip materials brought into the facility for routine testing.
For unexplained reasons, no OMA results were obtained during this peaked
enthalpy run. However, good polychromator data were obtained.

IV. DATA REDUCTION PROCEDURE

A. General

Because of resource constraints and data quality, it was decided to analyze only the OMA data from runs 91-020 and 91-024. The procedure was as follows. The 9-track digital tape recordings of the OMA data were first decoded using a program that interpreted the tape and stored the data on a temporary file. Then, a data correction routine was used to correct the raw data for variations in gain across the OMA screen. The proper correction factor was obtained by taking an OMA spectrum of the output of the tungsten standard lamp and using the published output of the lamp as a function of wavelength to correct the measured output. These corrected raw data were then stored in a permanent archival file. A printout was then made of each spectral scan (500 channel intensities). This printout was visually examined to determine regions where arc-tunnel data were present.

Large (i.e., 26 x 18-cm) plots were then obtained of the selected OMA output scans for further analysis. Xerographicly-reduced examples of such OMA data scans are shown in Figure 5 for both calibration and arc-tunnel conditions during Run No. 91-020. Note the presence of three lines in the scans. The 5106 and 5153 Å lines were used in the following data analysis but the 5218/5220 Å doublet lines are also present and some remarks about their intensity will be made in a later report.

Measured line widths, Δ^m, and peak line intensities, I^m, were obtained by physical measurement of distances on the output plots. The background light intensity was subtracted off by taking the average background value on both sides of the lines and referencing the line intensity peak to this background intensity position. Line shift data, δ, were obtained by ascertaining the location of peak output on the arc-tunnel run plots and referencing this channel position to the position of the line in the pre- and post-run copper hollow-cathode plot. The distance between the two lines on the calibration plot was used as the plate factor (i.e., Å/mm) for converting the physical width and shift measurement into Å.
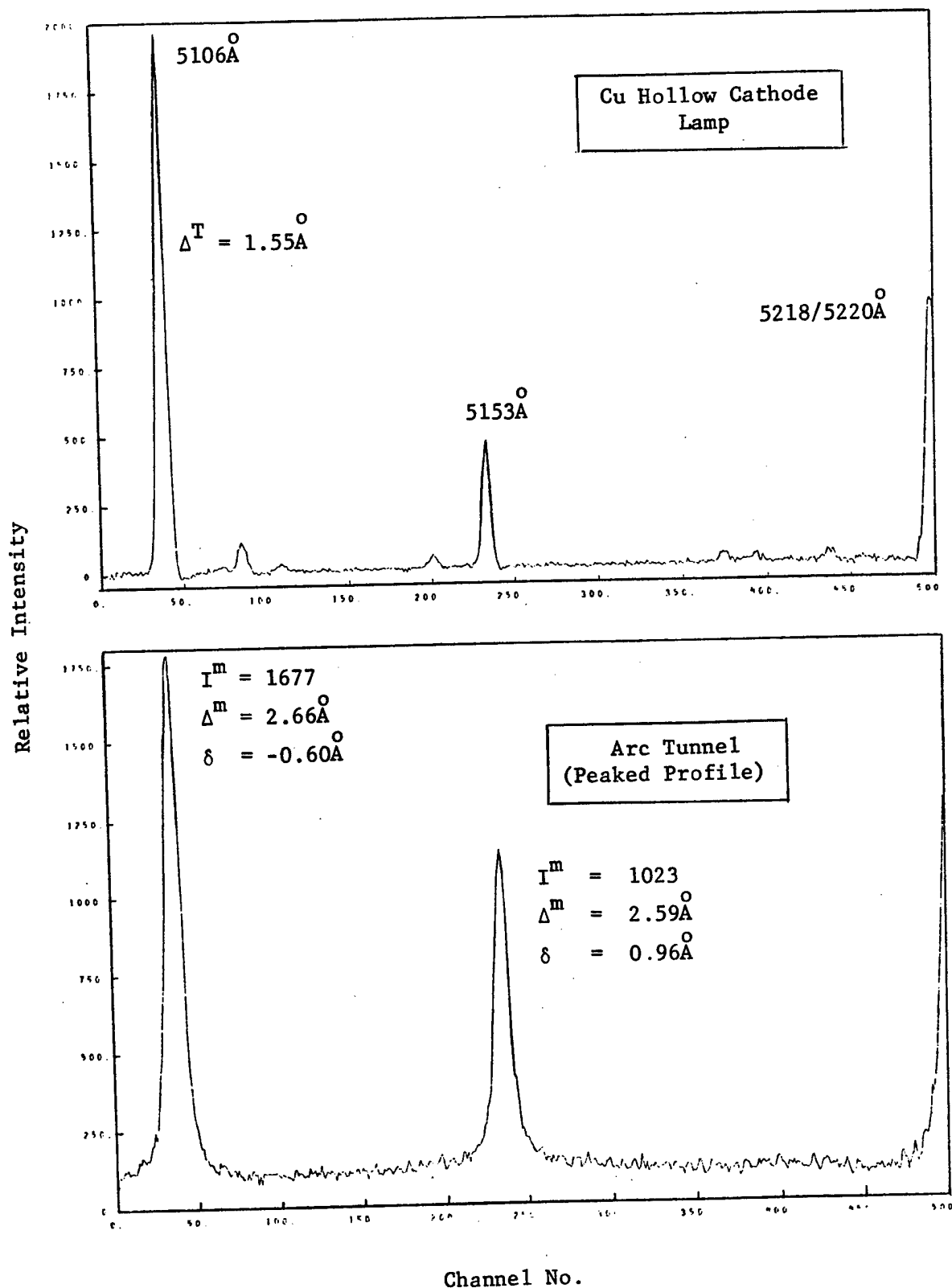
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FIGURE 5.   OMA DATA SCANS FOR CALIBRATION AND TEST
            CONDITIONS DURING RUN NO. 91-020
            ("PEAKED" ENTHALPY PROFILE)

Results of the above data reduction procedure for a given scan during Run No. 91-020 are shown listed in Figure 5 beside each line of interest. Ratios of I^m5106/I^m5153 and $\Delta^m5106/\Delta^m5153$ were computed and used for temperature and copper number density calculations.

B. Theory for Self-Absorption Corrections

Before temperature and number density could be obtained from the measured line width and intensity data, copper line intensity and line shape had to be calculated as a function of gas temperature, T, and copper density, N_{Cu}. The details of this theoretical procedure will not be presented here. It suffices to say that a theory which is normally attributed to Lindholm[5] was available to predict line intensity and shape for the above variables provided certain basic atomic constants are known. The theory for integrated line intensity ratio was coded into a digital computer program by AFFDL personnel in previous work.[3] This code was modified during the present study to include the determination of line shape and peak line intensity as a function of temperature and copper density.

The code first calculates the true line shape (i.e., infinitely-narrow instrument apparatus function) and plots the results of this calculation. However, since most spectral data are obtained with a finite slit width, some convolution will occur between the true and measured line shape in actual practice. Therefore, the code also includes the possibility of inputting a triangular-shaped instrument apparatus function with a full half-width, Δ^T, as a code input parameter. The convoluted line profile is then calculated and also plotted. The half-width and peak intensity of the true and convoluted line as well as the integrated line intensity are also calculated by the code and printed out on the line shape plot.

Some basic program inputs are the model pitot pressure, P_{t2}, and the length of the radiating gas region, ℓ, which is closely approximated by the model nose diameter. For the present analysis, P_{t2} = 80 atm and ℓ = 1.27 cm (1/2 inch) were used. Several assumptions were required for applying the above theory, namely:

- Temperature and copper density uniformity in the nose region

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- Radiatively inactive free stream
- Local thermodynamic equilibrium (LTE)
- Model stagnation pressure is constant.

A further assumption of an optically-thin gas-cap region was not required since the theory accounted for variations in copper density. This latter assumption is required for the simple optically-thin analysis of gas-cap temperature where self-absorption of copper radiation by other copper atoms is negligible. However, when self-absorption does occur, the copper density must also be measured and the optically-thin temperature must be corrected for self-absorption effects.

Results of the theoretical computation for peak intensity and line width ratio as a function of temperature and copper density are shown in Figure 6. This figure would have to be replotted for any change in run conditions that involved a change in ℓ, p, or Δ^T. The instrument apparatus function, Δ^T, used in the code calculation shown in Figure 5 was taken to be 1.55 Å. This value was obtained from the width of the 5106 Å line for the calibration conditions for Run No. 91-020 shown in Figure 5. It was assumed that the low-pressure copper lamp spectrum produced infinitely thin lines so that the convoluted line shape shown in Figure 5 was very nearly triangular and that the full half-width, Δ^T, was nearly that of the Jarrell-Ash instrument function itself.

C. Example Calculations

1. Temperature and Copper Density

To see how the curves of Figure 6 are used to infer temperature and copper density for Run No. 91-020, an example calculation can be performed using the data in Figure 5. Note from Figure 5 that

$$\frac{I^m 5106}{I^m 5153} = \frac{1677}{1023} = 1.64 \qquad ,$$

and
$$\tag{1}$$

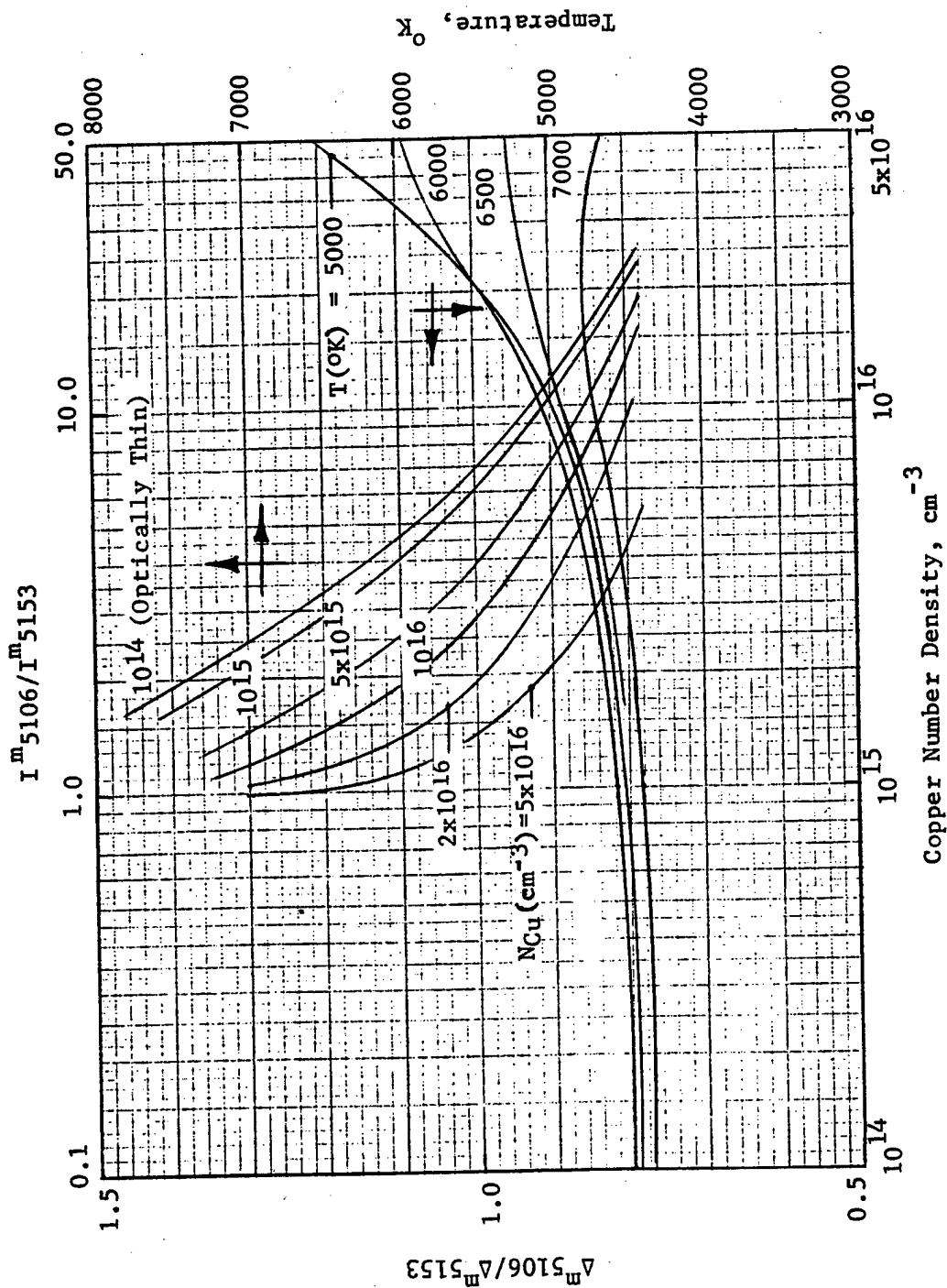$$\frac{\Delta^m 5106}{\Delta^m 5153} = \frac{2.66}{2.59} = 1.03 \qquad .$$

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FIGURE 6. THEORETICAL LINE INTENSITY AND WIDTH RATIOS FOR THE 5106 Å AND 5153 Å COPPER LINES AS A FUNCTION OF TEMPERATURE AND COPPER DENSITY. (p = 80 atm, ℓ = 1.27 cm, ΔT = 1.55 Å)

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Taking the value 1.64 for the ratio of peak intensities, and using the $N_{Cu} = 10^{14}$ cm^{-3} curve in Figure 6, the optically-thin temperature can be found directly. Hence,

$$T_{opt.thin} = 7800 \text{ K} \quad .$$

However, taking the value of line width ratio of 1.03 on the left side of Figure 6 and going across the plot horizontally, one finds that it does not intersect the family of curves for a temperature near 7800 K. Hence, the actual copper density must be greater than 10^{14} cm^{-3}. In other words, the gas cap is optically thick and some self-absorption has occurred. The $\Delta^m 5106 / \Delta^m 5153 = 1.03$ horizontal line does intersect the family of temperature curves for temperatures from 5000-6000 K and a copper density of near 2.5×10^{16} cm^{-3} (see Figure 6). Now, taking the $I^m 5106 / I^m 5153 = 1.64$ value on the top of Figure 6 and following vertically down the plot until a copper density curve near 2.5×10^{16} cm^{-3} is intersected (i.e., extrapolation between 2×10^{16} and 5×10^{16}), one can read across the plot to a temperature value of 5600 K. This is between the 5000-6000 K value indicated above, yielding a consistent set of data, namely:

$$\left.\begin{array}{l} \dfrac{\Delta^m 5106}{\Delta^m 5153} = 1.03 \\[2em] \dfrac{I^m 5106}{I^m 5153} = 1.65 \end{array}\right\} \text{ and } \left\{\begin{array}{l} T_{opt.thick} = 5600 \text{ K} \\[2em] N_{Cu} = 2.5 \times 10^{16} \text{ cm}^{-3} \end{array}\right. \qquad (2)$$

The accuracy of the above temperature and copper density determination could be improved somewhat by using a least square fit of the line profile data. At this point, however, it suffices to say that the value determined using this interpolation and iteration method is probably within 5 percent of what the curve-fit procedure would indicate. This 5 percent estimate was obtained by performing such a curve-fit analysis for the OMA line scan given in the above example. The results are shown in Figure 7. Note that the entire measured convoluted line shape for both copper lines agrees well with theory. The 5106 and 5153 Å line width values of 2.73 and 2.64 Å,
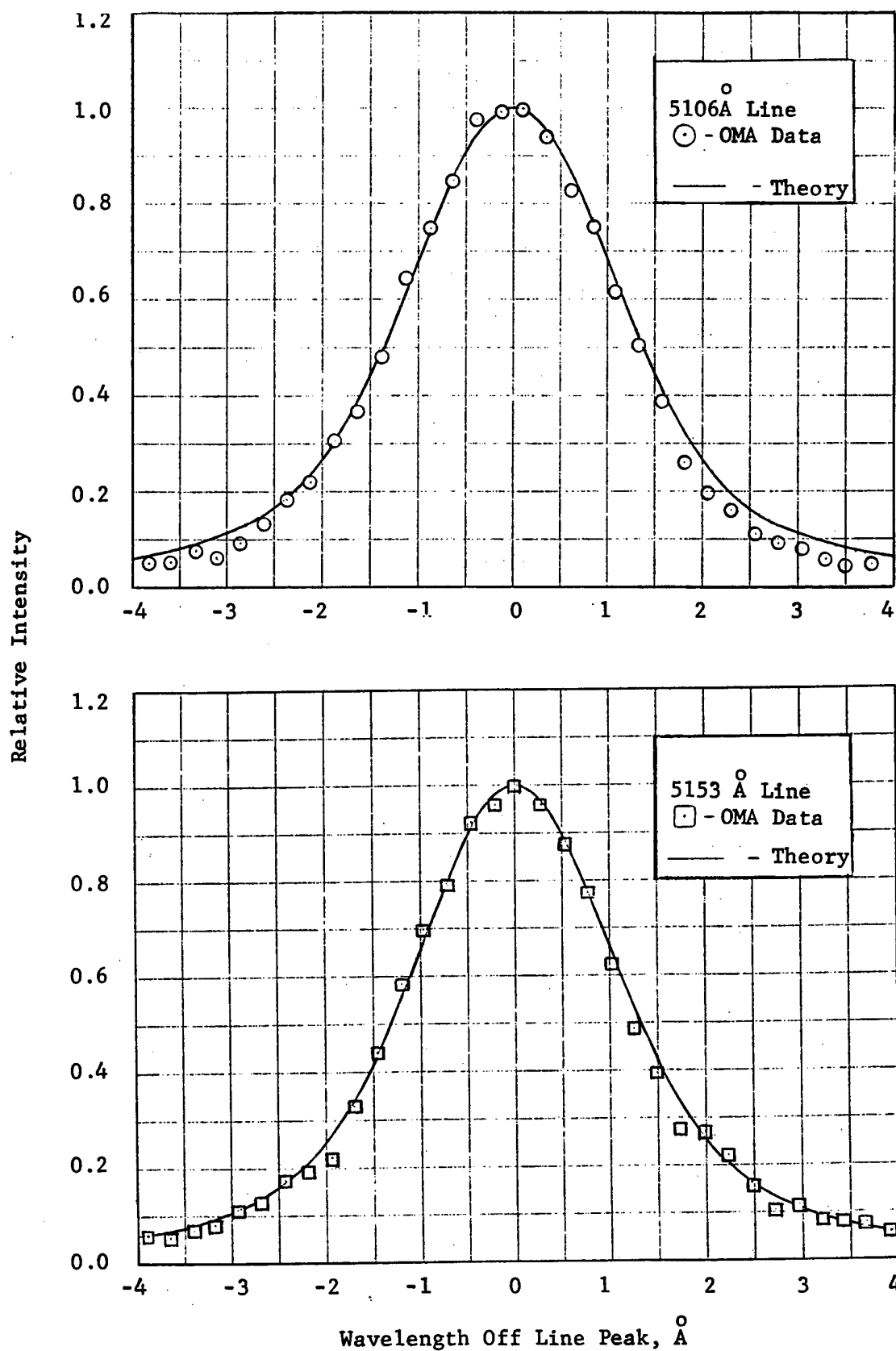
FIGURE 7. COMPARISON OF AN OMA DATA SCAN WITH THEORY FOR THE SHAPE AND
WIDTH OF THE 5106 Å AND 5153 Å COPPER LINES
$(T = 5600° K, N_{Cu} = 2.5 \times 10^{16} cm^{-3})$

respectively, determined from this curve fit procedure of Figure 7 are in excellent agreement with results given in Figure 5. The largest error was 3 percent for the measured width and the width ratio error was less than 1 percent when comparing the curve-fit procedure with the straight-forward measured line width procedure.

Another check on the accuracy and consistency of this result can be obtained by using the actual absolute value of the measured 5106 Å line width to indicate how well the theoretical line width agrees with this measurement for the temperature and number density values determined using Figure 6. To do this, Figure 8, which is a plot of the theoretical width of the 5106 Å line as a function of temperature and copper density, is used. For a temperature of 5600 K and $N_{Cu} = 2.5 \times 10^{16}$, a theoretical width of 2.75 Å is obtained. This value is within 3.5 percent of the measured value of 2.66 Å. Hence, the above values for temperature and copper density are also consistent with absolute line width measurements. By repeating this data reduction process for all the data for Run No. 91-020, the temperature and copper density history can be plotted for each model as a function of time.

2. Line Shift-to-Width Ratio Determination

Another parameter of importance in defining the copper line spectrum is the shift of the lines divided by their full half width. According to Lindholm's theory[5], the ratio of shift-to-width does not depend on the interaction constants or the densities of the perturbing particles but is determined by the law of interaction of the colliding particles. Therefore, a measurement of shift and width of lines can be used to carry out a quantitative test of the theory to verify that it does in fact apply to the collisional broadening of a given line. The absolute magnitude of the line shift itself is also important from the standpoint of deciding how the polychormator will respond to line position variations. Theoretical values for this shift/width ratio have been determined for optically-thin lines. These ratios have also been confirmed for the 5106-Å line in a 1-atmosphere arc by Ovechkin[6].
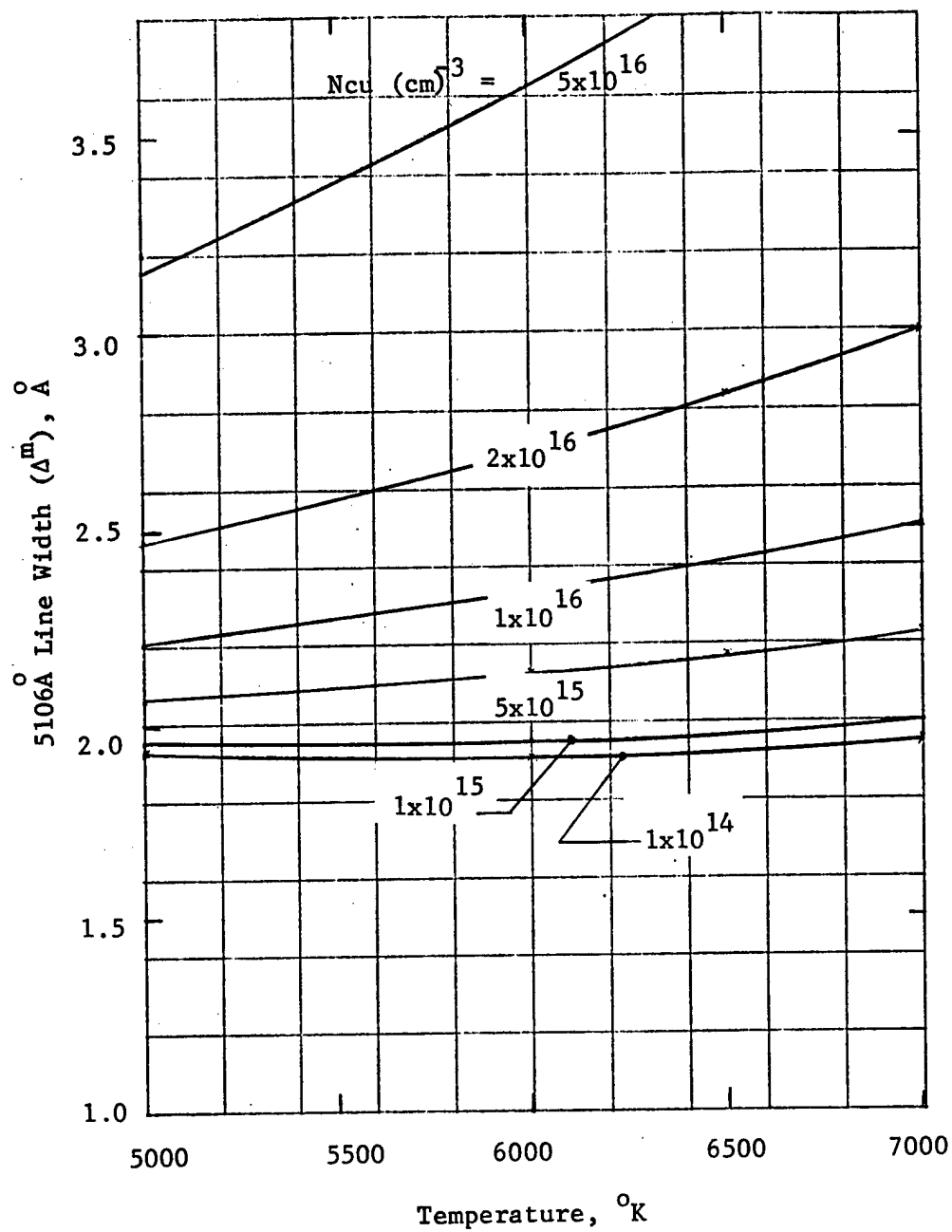
FIGURE 8.   THEORETICAL WIDTH OF THE 5106 $\overset{\circ}{A}$ COPPER LINE
AS A FUNCTION OF TEMPERATURE AND COPPER
DENSITY (p = 80 atm, ℓ = 1.27 cm, Δ^T = 1.55 $\overset{\circ}{A}$)

In order to deduce this parameter from the raw data, it was first necessary to determine the true line width, Δ^{ℓ}. This was done by knowing the measured convoluted line width, Δ^m, and the apparatus function width, Δ^T. The true line width was then determined using Figure 9. In this figure, the ratio of measured-to-appartus widths is plotted as a function of apparatus-to-true widths. The open circles are for triangular-shaped lines and apparatus functions. This curve was calculated as a closed-form solution. The filled symbols represent computer calculations assuming triangular apparatus functions but Gaussian-shaped lines. Because the measured lines were approximately Gaussian-shaped, the dashed line was used to deduce the true line shape. For example, the data in Figure 5 indicate that $\Delta^m/\Delta^T = 1.72$ and 1.67 for the 5106 and 5153 lines, respectively. Hence, the true width using Figure 9 would be

$$\Delta 5106 = 1.67 \ \overset{\circ}{A}$$

$$\Delta 5153 = 1.57 \ \overset{\circ}{A} \quad . \tag{3}$$

Using the line shift data in Figure 5 and the line width data in Equation (3), the shift-to-width ratio for this example would be

$$\left.\begin{array}{l} (\delta/\Delta)5106 = -0.36 \\[1em] (\delta/\Delta)5153 = 0.61 \end{array}\right\} \text{ present data} \quad . \tag{4}$$

Ovechkin reports

$$\left.\begin{array}{l} (\delta/\Delta)5106 = 0.357 \\[1em] (\delta/\Delta)5153 = 0.200 \end{array}\right\} \text{ opt. thin} \tag{5}$$

for optically-thin conditions. A comparison of Equations (4) and (5) indicates that there is signficant disagreement between the shift-to-width values determined in the present experiments and those measured by Ovechkin under optically thin conditions.
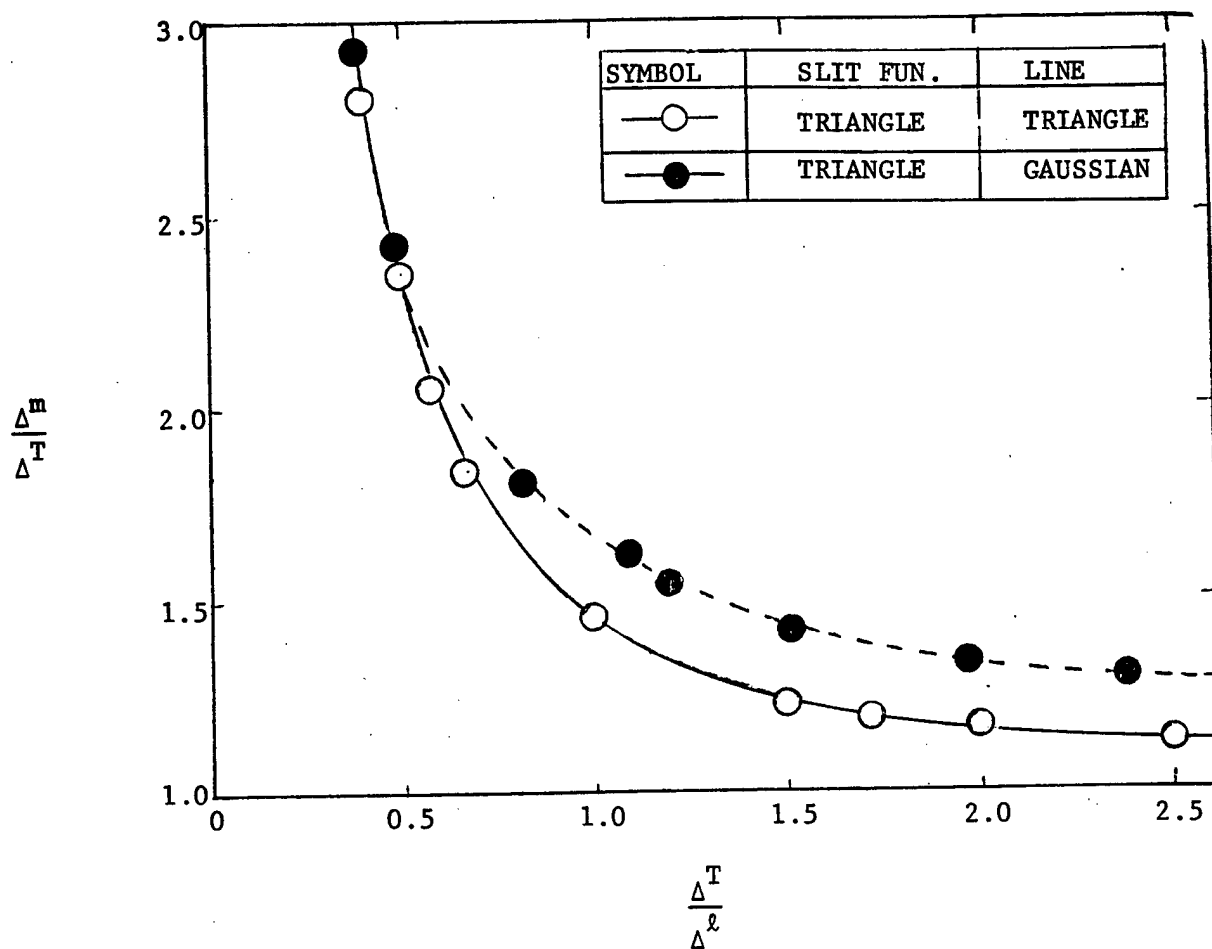
FIGURE 9. PLOT USED TO DETERMINE TRUE SPECTRAL LINE WIDTHS
FROM MEASURED VALUES USING RATIOS INVOLVING THE
INSTRUMENT APPARATUS FUNCTION WIDTH

V. EXPERIMENTAL RESULTS AND DISCUSSION

The data reduction procedure outlined in Section IV was performed for all the pertinent data for Run No. 91-020. Optically-thin temperature and temperature corrected for self-absorption effects are plotted in Figure 10 as a function of tunnel run time during model injection. The presence of a model in the flow is also indicated using time bars in Figure 10.

Data for Models 1 and 2 were sparse due to the fact that adjustments had to be made for the value of the neutral-density filter in front of the entrance slit because several overflow conditions occurred during these model dwell times. Once things were properly adjusted, more useful data were obtained for Models 3 and 4. Note that in Figure 10 the average optically-thin gas-cap temperature of 7425 K is 33 percent greater than the average corrected temperature value of 5600 K. Also, note that the standard deviation in the indicated temperature is approximately 1.5 times less for the corrected temperature values.

The above temperature results imply the following prediction of the average stagnation enthalpy by using thermodynamic data in reference (7).

$$(H_o) \text{ optically thin} = 6850 \text{ Btu/lb}_m$$
$$(H_o) \text{ actual} = 4275 \text{ Btu/lb}_m \quad . \tag{6}$$

Hence, the optically-thin enthalpy is 60 percent greater than that determined from a stagnation temperature corrected for self-absorption effects.

In Figure 11, the corresponding copper number density results are presented for Run No. 91-020. Note that the average measured copper density of $2.5 \times 10^{16} \text{ cm}^{-3}$ is more than two orders of magnitude greater than the density required to support the optically-thin approximation. It can also be said that fluctuations in copper density evident in Figure 11 are partially responsible for the increased fluctuation in the measured optically-thin temperature in Figure 10. These copper density measurements are also an indication of the arc flow quality for Run No. 91-020 and can be used for this purpose as well.
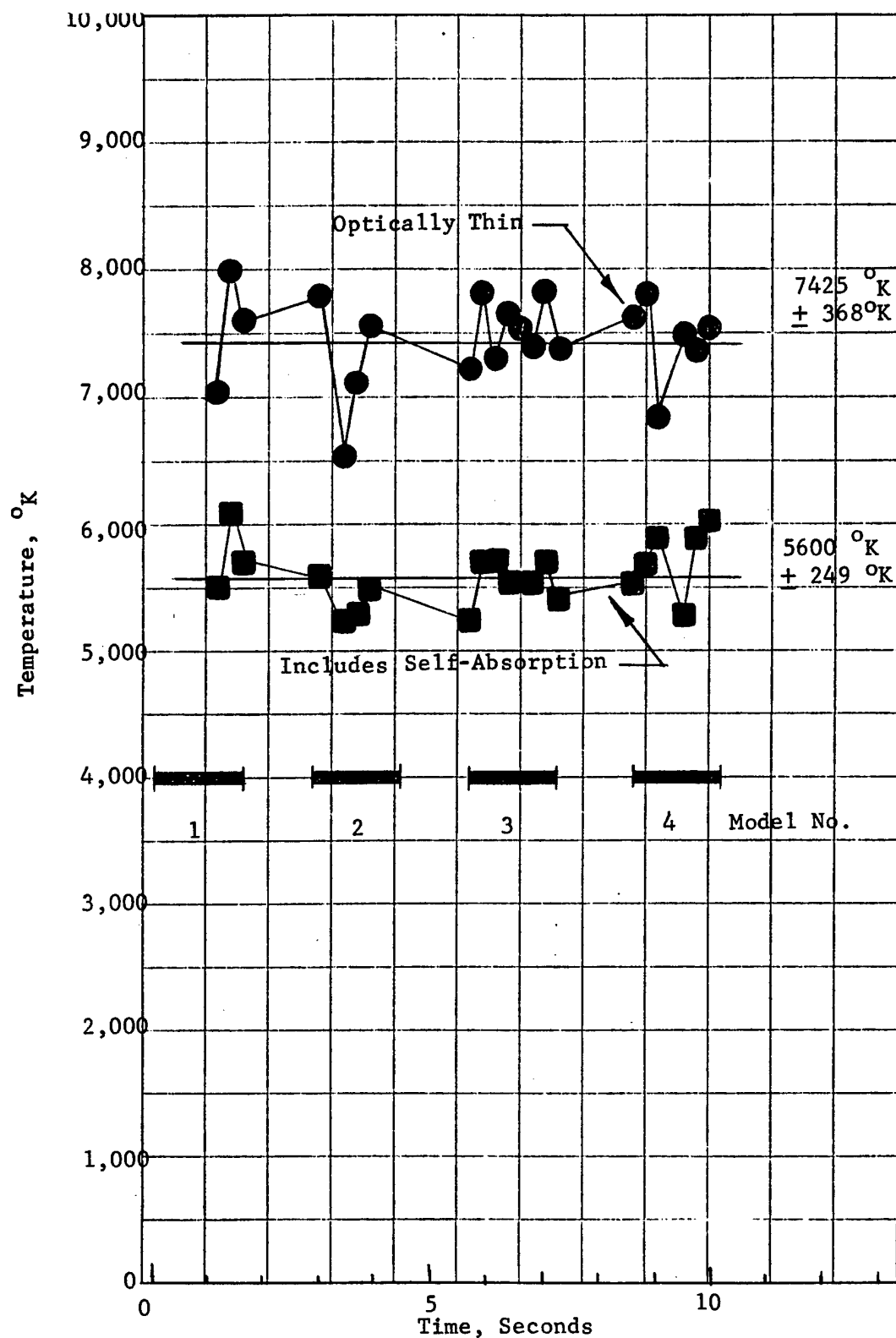
FIGURE 10.   RESULTS OF THE GAS CAP TEMPERATURE MEASUREMENTS FOR THE
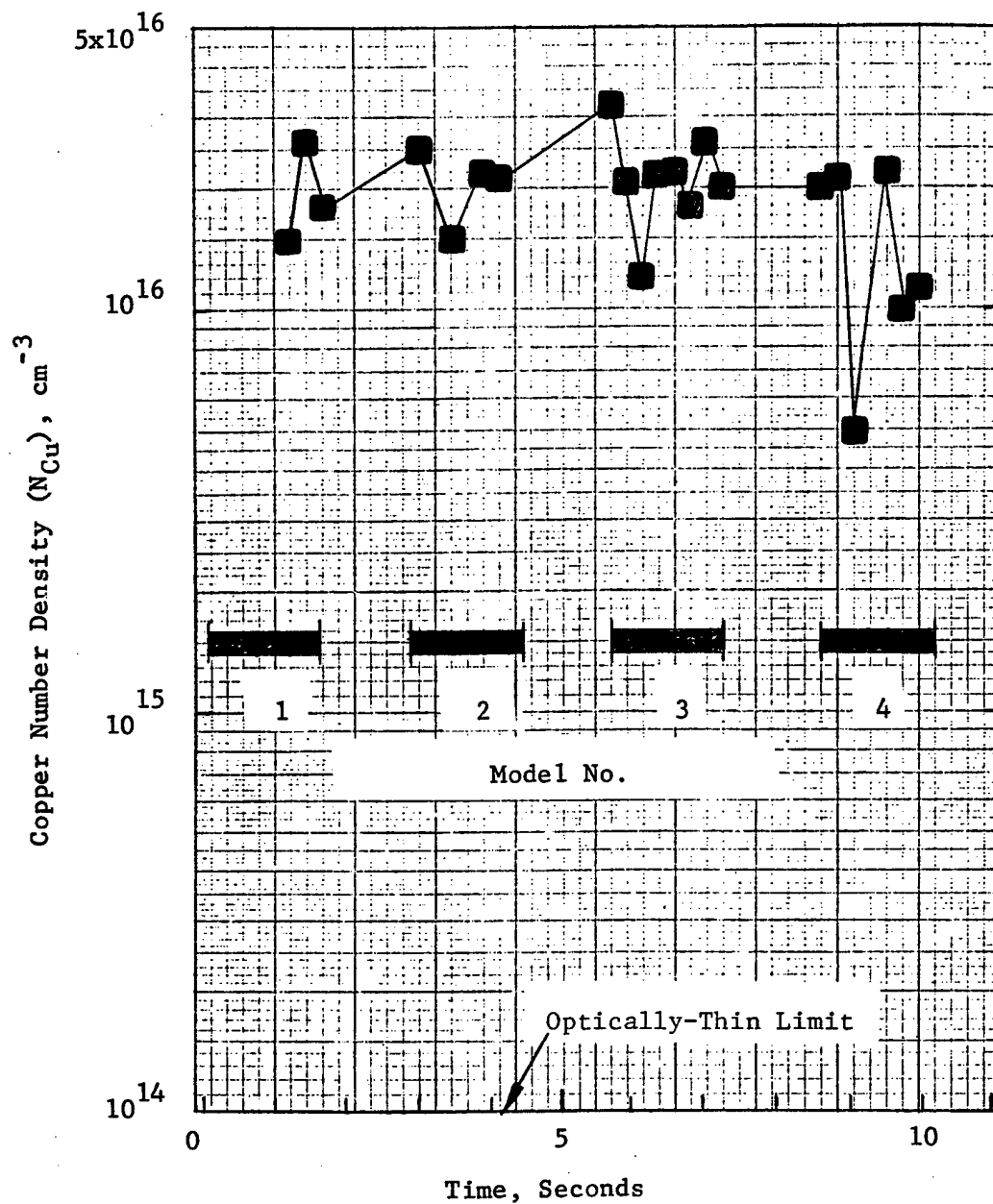   "PEAKED" ENTHALPY PROFILE RUN NO. 91-020

FIGURE 11. COPPER NUMBER DENSITY MEASUREMENTS DURING THE "PEAKED" ENTHALPY PROFILE RUN NO. 91-020

Results of the shift-to-width ratio measurements for Run No. 91-020 are shown in Figure 12 for both the 5106 and 5153 Å lines. These results indicate that the example calculations of Equation (4) are representative of the average value of all the data from this tunnel run. Also shown in Figure 12 are the values of δ/Δ for Vanderwall's broadening, (δ/Δ) vw = +1/2.8, and stark broadening, $(\delta/\Delta)_s$ = +1/1.16 obtained from Lindholm's theorgy for optically thin conditions[5]. The 5106 line shift-to-width ratio certainly cannot be considered normal since the shift is opposite in sign to that indicated by the shift paramaters given in Reference 6. The 5153 line does, however, fall in the region of the application of Lindholm's theory. This apparent difference for the shift of the 5106 Å line cannot be explained at this time.

Theoretical line-shape plots for the two lines at the average temperature and copper density conditions for Run No. 91-020 are shown in Figure 13. Note that the 5106 line shape is definitely non-Gaussian as compared to the 5153 line. Indeed, these calculations show that the 5106 line was more affected by self-absorption in the gas cap than was the 5153 Å line. Note also that the theoretical calculations for true line width, Δ^ℓ, can be obtained from Figure 13. Comparing these calculations with the inferred measured line width given in Equation (3), we find that for the 5153 Gaussian-shaped line the inferred line width of 1.57 Å is in good agreement with the theoretical true line width of 1.68 Å. This fact lends support to our method of obtaining true line width using Figure 9 to correct the actual measured line width, Δ^m, given in Figure 5.

Also note that for the non-Gaussian 5106 line the agreement is not as good (i.e., Δ^ℓ calc = 2.06 and Δ^ℓ meas = 1.67 or a 19 percent error). This error can be expected since the theory associated with computing the correction curve in Figure 9 assumed a Gaussian line shape. This relatively small error would not change the results shown in Figure 12 to any appreciable extent [δ/Δ = -0.29 instead of -0.36 as given in Equation (4)], so the statements regarding the anomalous shift of the 5106 line are still valid.
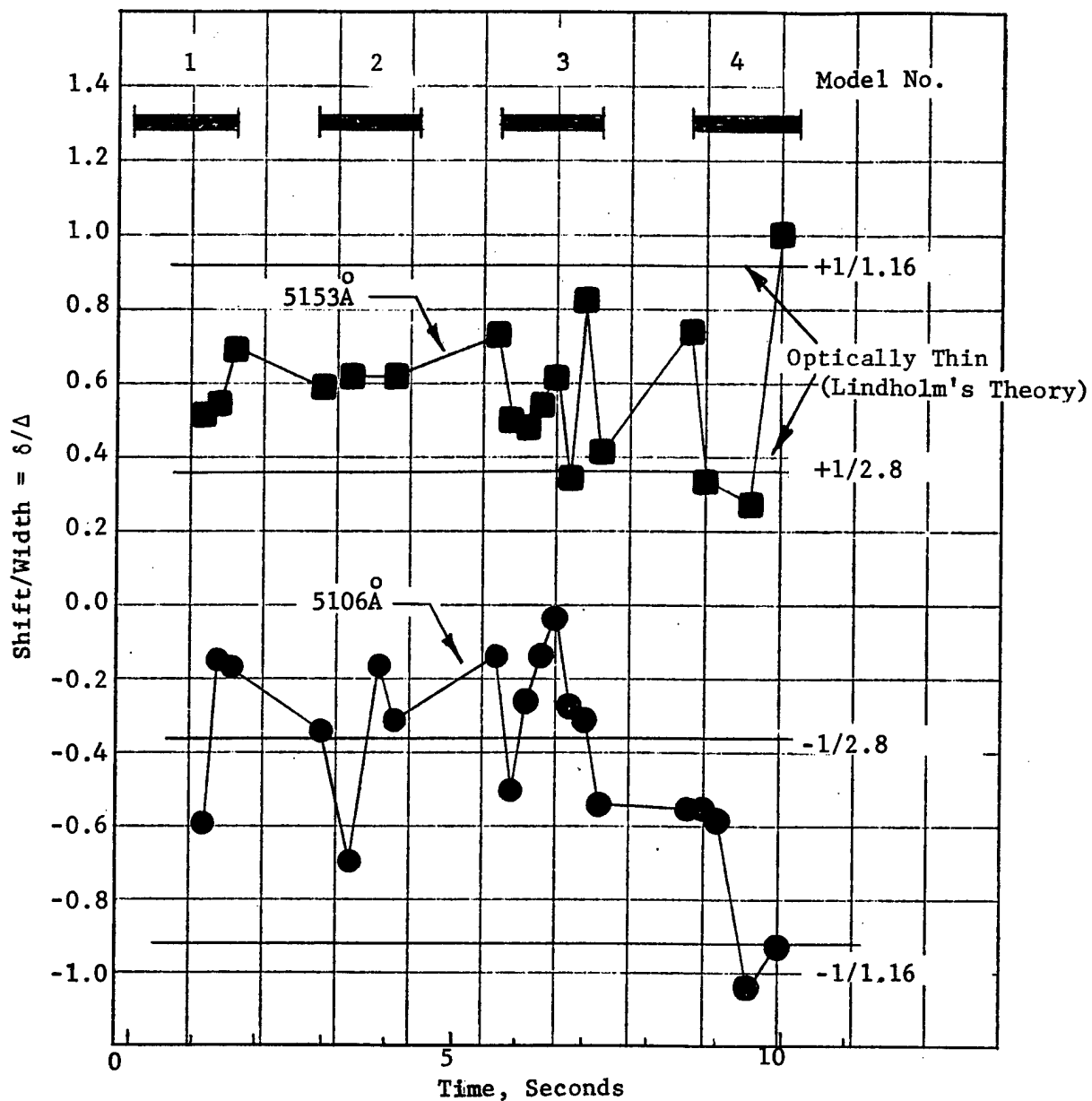
FIGURE 12.   5106 AND 5153 Å LINE SHIFT-TO-WIDTH RATIO MEASUREMENTS
FOR RUN NO. 91-020 COMPARED TO LINDHOLM'S THEORY FOR
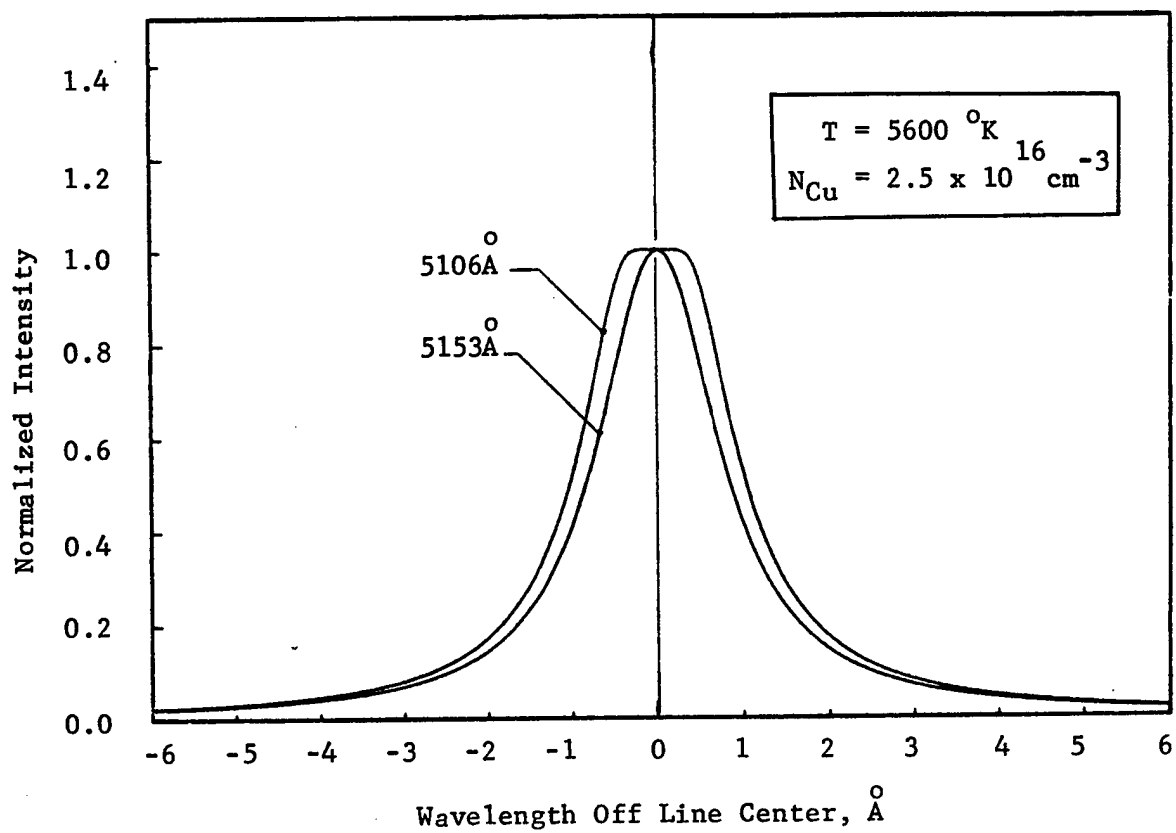OPTICALLY THIN CONDITIONS

FIGURE 13. TRUE THEORETICAL LINE SHAPES FOR THE 5106 Å AND
5153 Å COPPER LINES FOR CONDITIONS TYPICAL OF
RUN NO. 91-020

OMA data were also obtained for a "flat" profile run (i.e.,
No. 91-024). A typical data scan indicating gas-cap copper emission
spectra for this run is shown in Figure 14. Note that only the 5106 line
is measurable for this arc-tunnel condition because the 5106 Å line intensity
is estimated to vary as the sixth power of temperature and the gas tempera-
ture is estimated to be much lower (i.e., $T \approx 3500$ K) for this run condition.
Furthermore, the 5106/5153 line intensity ratio is an order of magnitude
greater for this lower temperature condition. From Table 2 it can be seen
that the shutter time was the same but the slit-width and slit-neutral-density
filters were different for the two runs. Taking these factors into account,
the 5106 line intensity for the peaked profile run (i.e., No. 91-020) was
determined to be approximately 15 times greater than that of the flat profile
run (i.e., No. 91-024). Hence the 5153 line was approximately 150 times
greater for the peaked profile case over that for the flat profile conditions.

Since only one line was measured, no temperature data could be
obtained from Figure 14. However, line shift and width information could
still be determined as indicated in this figure. These calculations showed
that

$$\Delta^{\ell}5106 = 1.92 \text{ Å}$$

$$(\delta/\Delta)5106 = 0.076$$

(7)

for the data in Figure 14. Such line shape and shift data were obtained
for all the usable OMA scans in Run No. 91-024. These data are shown plotted
in Figure 15. Note that the δ/Δ values are closer to, but still not in
agreement with, the Lindholm theoretical values for optically thin conditions.
In this case, however, the broadening due to self-absorption probably caused
most of the disagreement rather than the anomalous line shift. Also, note
that only five scans had a sufficiently high signal-to-noise ratio to deem
them usable for data reduction purposes.

Assuming that the gas-cap temperature was 3500 K, the corres-
ponding copper density can be calculated from the average true line width
of 1.77 Å $\pm$ 0.92 Å. A value of $N_{Cu} = 7 \times 10^{16}$ cm^{-3} was determined from
these theoretical line-width calculations. This copper density value is
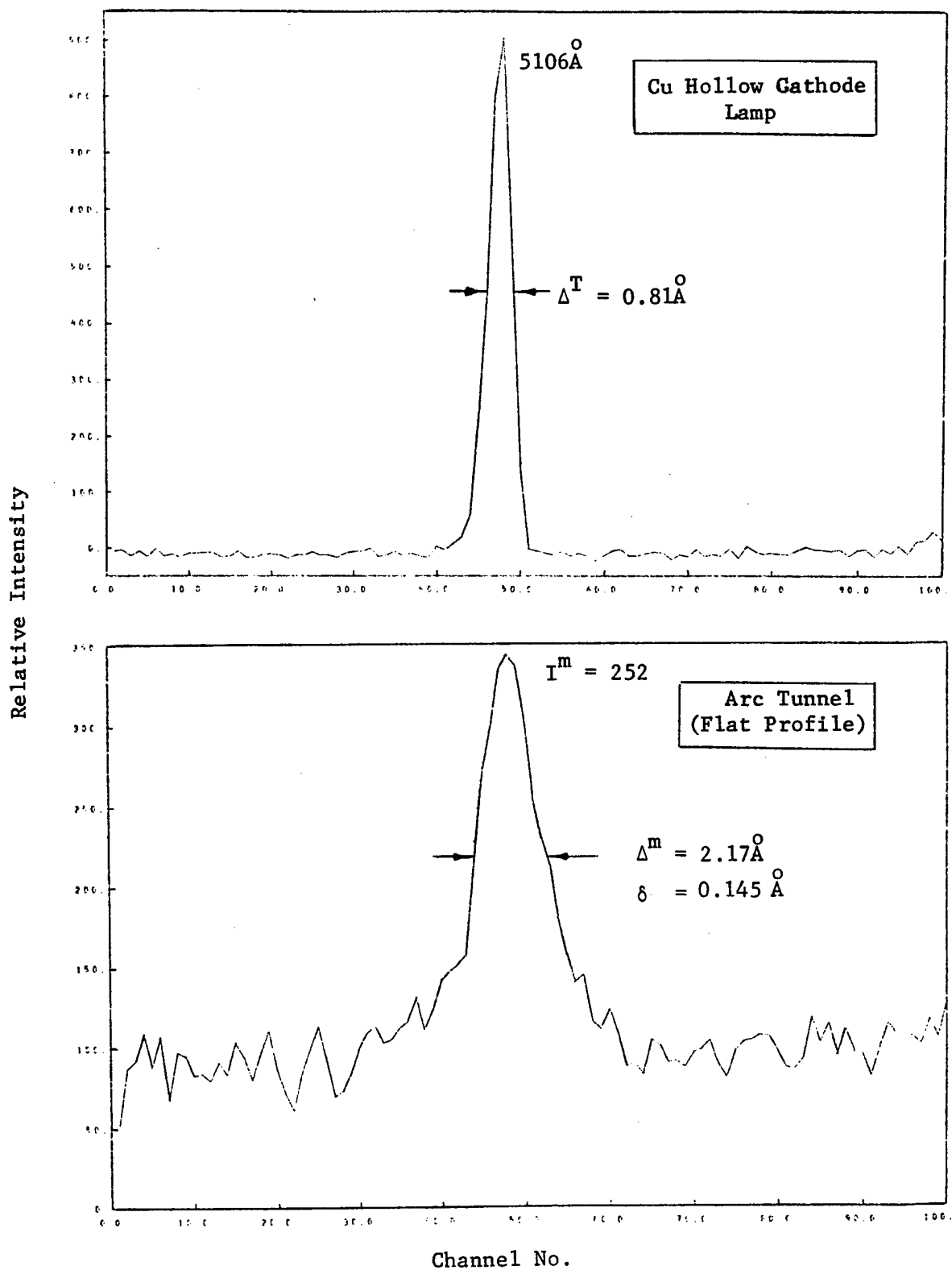
FIGURE 14. OMA SCANS FOR CALIBRATION AND TEST CONDITIONS
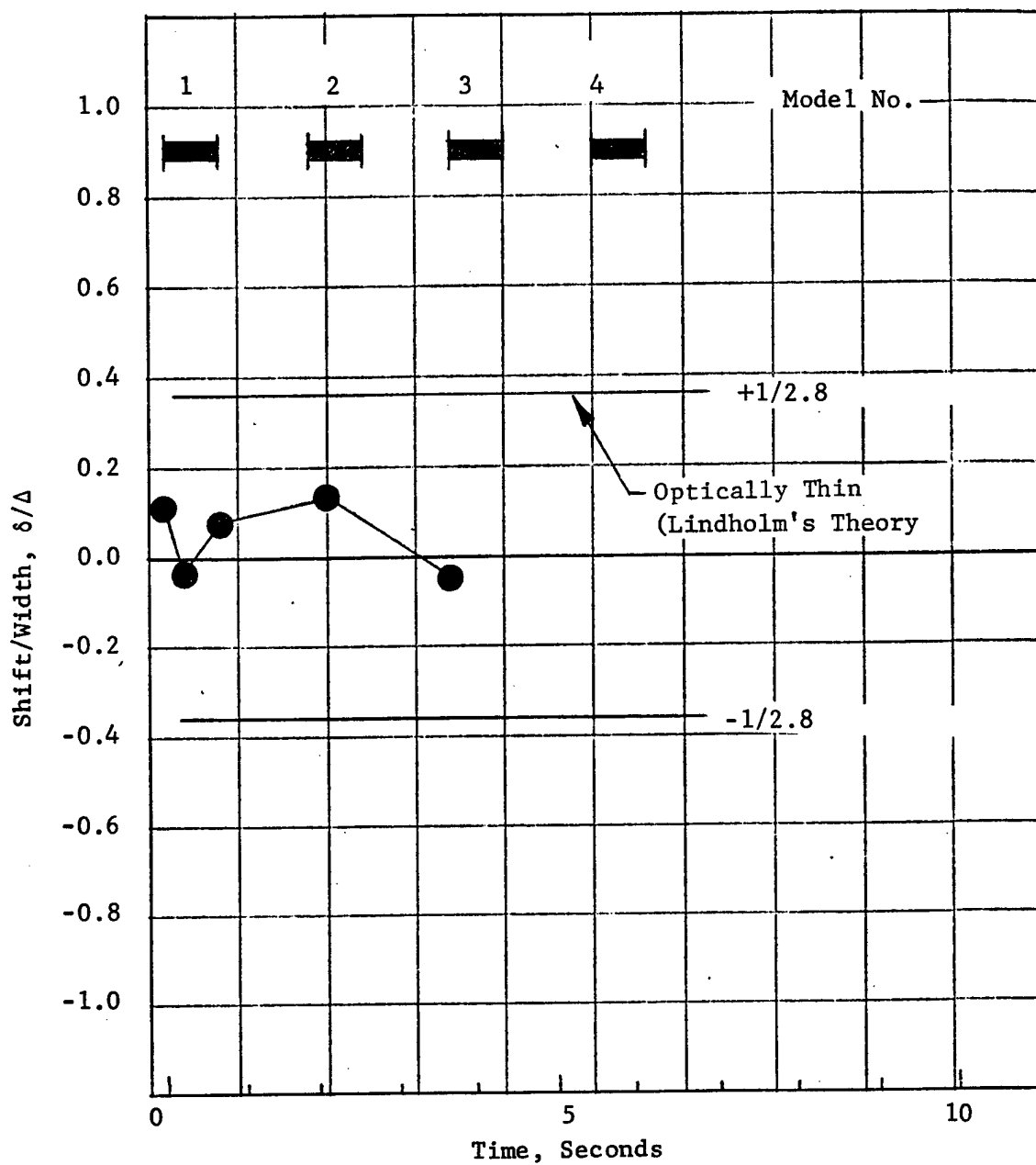DURING RUN NO. 91-024 ("FLAT" ENTHALPY PROFILE)

FIGURE 15.   5106 Å LINE SHIFT-TO-WIDTH RATIO MEASUREMENTS FOR
RUN NO. 91-024 COMPARED TO LINDHOLM'S THEORY FOR
OPTICALLY THIN CONDITIONS

in good agreement with that inferred from the factor of 15 absolute line intensity variation between Run No. 91-020 and No. 91-024. Hence, the copper spectra data also seem consistent with optically-thick theory for the "flat" profile run condition.

One of the objectives of the current measurement sequence was to obtain simultaneous OMA/polychromator data in order to compare these two techniques for obtaining raw line intensity data. The purpose of this comparison was to guide later efforts that will involve designing the final version of an instrumentation package to make routine stagnation temperature measurements. Although no simultaneous data were obtained, the OMA results can still be used to infer the probable polychromator performance. This inference is possible because the OMA data can be used to indicate the true line shift and shape of the copper lines of interest. These shape and shift data can then be compared to the actual polychromator apparatus function, shape, and spectral position. To facilitate this inference, results of the OMA data scan shown in Figure 5, which turned out to be typical of Run No. 91-020, are shown in Figure 16 (see Figure 13). Also shown in Figure 16 is the approximate trapezoidal apparatus function of the polychromator used in this experiment and in previous work by AFFDL[3].

Note that the actual lines are significantly broader than the apparatus function--especially in the wings of the lines. Also note that the average measured line shift for the two lines is significant compared to the center of the polychromater apparatus function. These two combined effects imply that line intensity output measured by the polychromator was significantly less than the true intensity. Because the theory associated with the polychromator assumes that the total integrated line intensities are being measured, errors will result if some method is not used to correct this shift and shape-change problem.

Because each line shifted in about the same amount for this particular tunnel run condition, the error associated with the overall ratio of the two lines, which is used to infer temperature, was less than that for absolute intensity error of each line. However, this was somewhat fortuitous and inaccuracies will still result in the final temperature measurement due to these effects. Also, the absolute line intensity for the 5106 line is required for self-absorption corrections using the polychromator
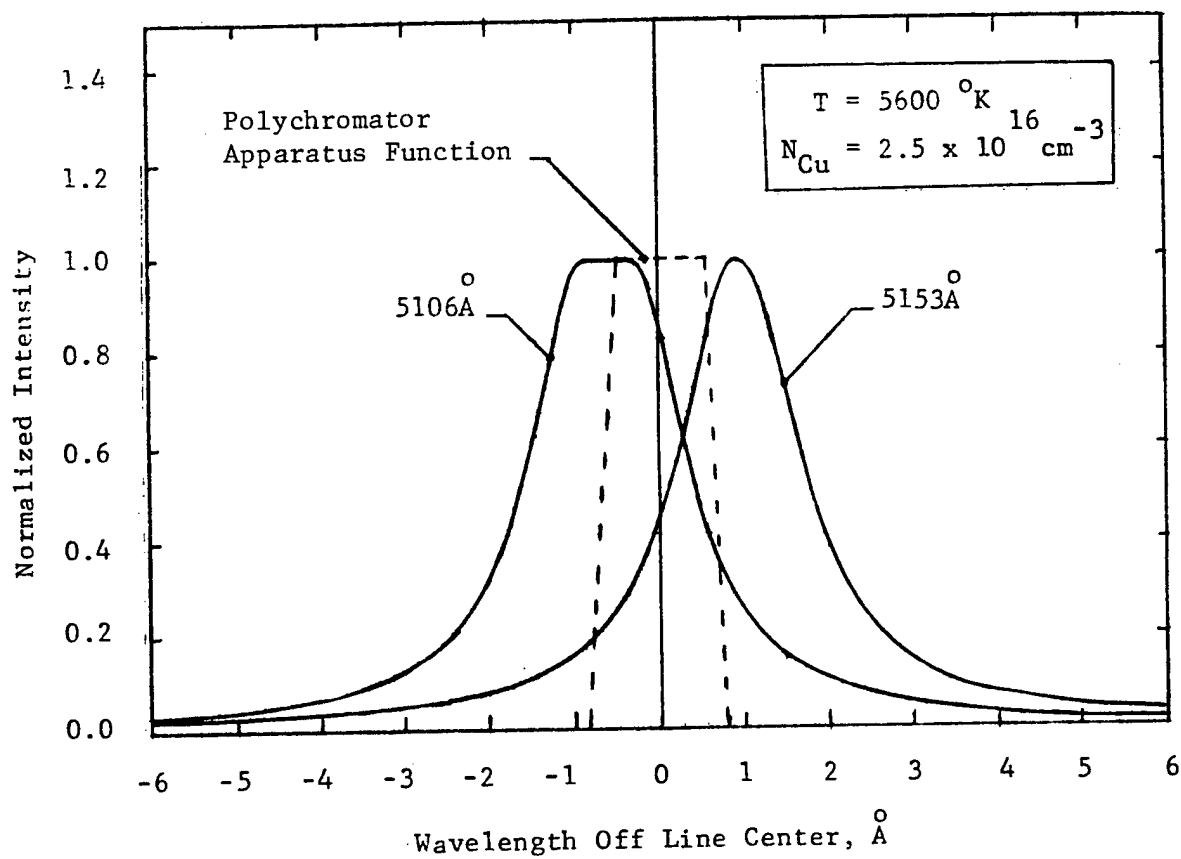
FIGURE 16. INDICATION OF POLYCHROMATOR PERFORMANCE FOR
AVERAGE LINE SHIFT AND SHAPE CONDITIONS
DURING RUN NO. 91-020

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technique. Hence, improper corrections will result using the present polychromator scheme. A combination of the above shape and shift effects probably caused the large fluctuations in intensity output evident in past and present attempts to obtain polychromator data.

Even though the present polychromator method has some significant problems associated with obtaining accurate line intensities, the technique has one significant advantage in that continuous data can be obtained using this method while the OMA is presently limited to approximately five data points per second. This continuous data gathering capability would provide more information on variations in stagnation temperature during a particular model dwell time.

Hence, a combination of the two techniques might be most appropriate. The polychromator apparatus function could be preshifted for each line using the copper hollow-cathode lamp and the OMA to accurately guide the adjustment of polychromator slit positions. The accuracy of this position setting is estimated to be within $\pm$ 0.1 Å of the expected line shift. The apparatus function could also be broadened, especially at the base, in order to more nearly correspond to the expected line shape during arc-tunnel operation. Simultaneous OMA and polychromator data would then by obtained with the OMA data being primarily used to verify that the predicted shift and shape changes were, in fact, realized. Both methods could then be used to obtain stagnation temperature corrected for self-absorption. Either the measured copper density determined from the OMA line-shape results or the polychromator output for the continuous absolute 5106 line intensity could be used to correct the polychromator data for self-absorption effects. If the preset polychromator position shifts are not adequate for a particular tunnel run, then the OMA data alone would suffice to indicate the average stagnation temperature for a particular run.

VI. CONCLUSIONS

In this study, a comparison was made of Lindholm's theory with the measured line intensities, shape, and shifts of the 5106 and 5153 Å copper lines during arc-tunnel operation. The theory was then used to infer temperature and copper number density from these spectral measurements. Data were obtained for both "flat" and "peaked" enthalpy profile conditions. Based upon the above results, the following conclusions are applicable for the "peaked" enthalpy run condition:

(1) The absolute 5106 Å line width, ratios of 5106 to 5153 Å line widths, ratios of 5106 and 5153 peak line intensities, and overall shape of the convoluted line profiles were all consistent with predictions based on Lindholm's theory. This does not conclusively prove that Lindholm's theory, as coded into our data reduction routine, applies to the actual RENT environment. However, the consistency certainly lends support to the argument that it does apply. Line-shape measurements using higher spectral resolution should prove helpful in providing further checks to this theory. The results of contract efforts by CALSPAN to check Lindholm's theory for the copper lines of interest under known thermodynamic conditions may also provide additional insight with regard to the application of Lindholm's theory for conditions typical of the RENT environment.

(2) Line shift-to-width ratio measurements for the 5106 Å line were in poor agreement with values from Lindholm's theory assuming shift constants given in reference (6). This fact is not explainable at the present time and may have a pronounced affect on application of the copper line ratio technique for obtaining accurate enthalpy measurements in the RENT facility.

(3) Reduced line intensity data using Lindholm's theory showed that the average, measured copper density was two orders of magnitude higher than the optically-thin limit for a peaked enthalpy run condition (i.e., Run No. 91-020).

(4) Due to this high copper density encountered for the particular tunnel run of interest, significant self-absorption occurred which resulted in a 33 percent higher average value for the optically-thin measured temperature and a 60 percent higher enthalpy prediction than that obtained when self-absorption effects were included.

(5) The measured average enthalpy corrected for self-absorption effects was 4275 Btu/lb_m.

(6) Due to the anomalous 5106 $\overset{\circ}{A}$ line shift, an accurate error estimate for the above enthalpy measurement cannot be given at this time since the corrected enthalpy is dependent on the application of Lindholm's theory to account for self-absorption effects.

(7) The polychromator apparatus cannot be used alone to obtain accurate line intensities in the RENT peaked-profile environment. The OMA is required, in conjunction with the polychromator, to pre-shift and adjust the polychromator apparatus function position to better enable this instrument to obtain true integrated line intensity data. The OMA output is also required to check that the preset position values are valid during the actual tunnel run and to obtain an independent measure of the copper number density and temperature during the test.

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From the "flat" enthalpy profile results, the following conclusions are applicable:

(1) The present copper line intensity method is not accurate at the flat enthalpy profile conditions due to the lack of line intensity data on the 5153 A line compared to background light levels. However, some other line combination might be found that would alleviate this problem.

(2) The measured 5106 peak line intensity and line width indicated a consistent value for measured copper density of 7×10^{16} cm^{-3} assuming a gas-cap temperature of 3500 K.

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